Arizona Geological Society Digest 22
2008

Fluid-inclusion evidence for the formation of Main Stage polymetallic base-metal veins, Butte, Montana, USA

Brian G. Rusk*
US Geological Survey, MS 963, Denver, Colorado, 80225, USA

Brooke J. Miller
General Moly, Inc., Reno, Nevada, 89509, USA

Mark H. Reed
Department of Geological Sciences, University of Oregon, Eugene, Oregon, 97403, USA

ABSTRACT

The Butte porphyry Cu-Mo deposit is cut by the Butte Main Stage, a system of veins that constitute one of the world's largest Cordilleran-style base-metal lode deposits. The vein system is zoned from a central Cu-rich zone containing covellite, chalcocite, digenite, and enargite to an intermediate zone containing both Cu and Zn sulfides, to a peripheral zone dominated by sphalerite, galena, and rhodochrosite.

We examined fluid inclusions in ~50 veins from throughout the lateral and vertical extent of the deposit and conducted microthermometry on 13 of these samples. Fluid inclusions in Main Stage veins are similar in appearance throughout the central, intermediate, and peripheral zones such that only one type of fluid inclusion dominates all samples observed. At room temperature the fluid inclusions are liquid-rich, with 20 volume % bubble (B20 inclusions). Most inclusions analyzed contain between 1 and 4 wt. % NaCl equivalent, and between 0.2 and 1 mol % CO_2. Most inclusions homogenize to liquid between 250°C and 300°C. Even though there is considerable overlap, there is a weak trend from higher to lower homogenization temperatures and salinities from the central zone to the peripheral zone.

Vapor-rich inclusions are rare and were identified in only one Main Stage vein, thus, we infer that nearly all inclusions were trapped in the liquid field at pressures above the boiling curve. Maximum estimated depth of formation for Main Stage veins is 6 km. At such pressures, an isochoric temperature adjustment of up to about 50°C is required, indicating that most Main Stage veins formed at temperatures between about 250°C and 350°C.

We suggest that Main Stage veins formed where single-phase B60 fluids, which formed pre-Main Stage pyrite-quartz veins with sericitic alteration, decompressed and mixed with meteoric water in a hydrostatic pressure regime. Pre-Main Stage brines were not likely involved in Main Stage vein formation, and the role of pre-Main Stage vapor in the formation of Main Stage veins is not known.

e-mail: Rusk: brian.rusk@jcu.edu.au; Miller: brookemiller02@gmail.com; Reed: mhreed@uoregon.edu

*current address: School of Earth and Environmental Sciences, James Cook University, Townsville, Queensland, Australia, 4811

Rusk, B.G., Miller, B.J., and Reed, M.H., 2008, Fluid-inclusion evidence for the formation of Main Stage polymetallic base-metal veins, Butte, Montana, USA, *in* Spencer, J.E., and Titley, S.R., eds., Ores and orogenesis: Circum-Pacific tectonics, geologic evolution, and ore deposits: Arizona Geological Society Digest 22, p. 573-581.

INTRODUCTION

Butte, Montana got its name as "The richest hill on Earth" from the large base-metal veins that have been mined there for over 140 years. Base-metal veins in Butte were originally worked for Ag (and minor Au) in the latter part of the 19th century, but with the advent of the industrial revolution, Butte's vast Cu resources became increasingly important and have remained so ever since. Historically, most of the Cu mined from Butte was derived from polymetallic base-metal lodes known as "Main Stage" veins. However, since the opening of the Continental Pit in 1980, low grade disseminated Cu and Mo ore of the "pre-Main Stage" porphyry-type mineralization has been mined (Czehura, 2006). Since the first discovery of Au in 1864, Butte has produced over 10 Mt of Cu, 2.9 Mt of Zn, 1.7 Mt of Mn, and 0 .4 Mt of Pb (Long, 1995; Czehura, 2006).

Butte Main Stage veins are classified as Cordilleran base-metal lodes, which are characterized by wide sulfide-dominated veins, strong mineral zoning from a Cu-rich central zone outward to a Pb-Zn (Ag) peripheral zone, and advanced argillic or sericitic alteration (Einaudi,1994). Butte is a classic locality of a Cordilleran base-metal lode deposit, which are sometimes referred to as "Butte type" vein deposits (Einaudi et al., 2003). Like at Butte, many Cordilleran base-metal lodes are superimposed on the upper reaches of porphyry Cu deposits, and they are always younger than porphyry mineralization.

Superposition of porphyry-type and later epithermal deposits is common and has been recognized in numerous deposits around the world (Corn, 1975; Arribas et al., 1995; Hedenquist et al., 1998; Phillips et al., 1998; Ossandon et al., 2001; Muntean and Einaudi, 2001; Manske and Paul, 2002; Khashgerel et al., 2006). The common spatial coincidence between these two deposit types suggests a common origin, however conclusive evidence for a genetic link between porphyry-style and epithermal mineralization is rare (Hedenquist et al., 1998, Muntean and Einaudi, 2001). It is not clear at Butte whether the Main Stage and pre-Main Stage deposits represent a continuum of a single hydrothermal system formed from the same heat and fluid source, but under different physical and chemical conditions, or whether the Main Stage vein system formed at a later time from a separate heat and fluid source. These two hypotheses have dramatically different implications for understanding the ore deposit genesis and for predicting undiscovered resources.

Although numerous studies of the geology and mineral zoning of Main Stage veins exist, few fluid inclusions of the Main Stage vein system exist (Roedder, 1971; Miller, 2004; Rusk et al., 2008). We use fluid inclusions to constrain the variations in pressure, temperature, fluid salinity, and gas content in Main Stage vein samples that span the mineral zones laterally and vertically. Our results, combined with previous fluid inclusion studies of pre-Main Stage veins and geologic relations among pre-Main Stage and Main Stage veins, elucidate the origin of the base metal lodes and yield insight into their relationship to the porphyry Cu-Mo system at Butte.

GEOLOGIC BACKGROUND

The ore deposit at Butte lies within the Butte Quartz Monzonite at the southern end of the Boulder batholith in southwestern Montana, USA (Fig. 1). The deposit is centered on an E-W-striking swarm of quartz-porphyry dikes that accompanied the injection of hydrothermal fluids at the initiation of the porphyry Cu ("pre-Main Stage") hydrothermal system at Butte. Porphyry-related mineralization is inferred to have formed at greater depth than in most porphyry Cu (Mo-Au) deposits (Roberts, 1973, 1975; Rusk et al., 2008). The pre-Main Stage Cu- and Mo-bearing veinlets are universally cut by the large through-going "Main Stage" base-metal vein lodes.

Pre-Main Stage mineralization

Pre-Main Stage veinlets are narrow (a few mm to a few cm) quartz ±sulfide veinlets with potassic or sericitic alteration similar to porphyry Cu mineralization from numerous

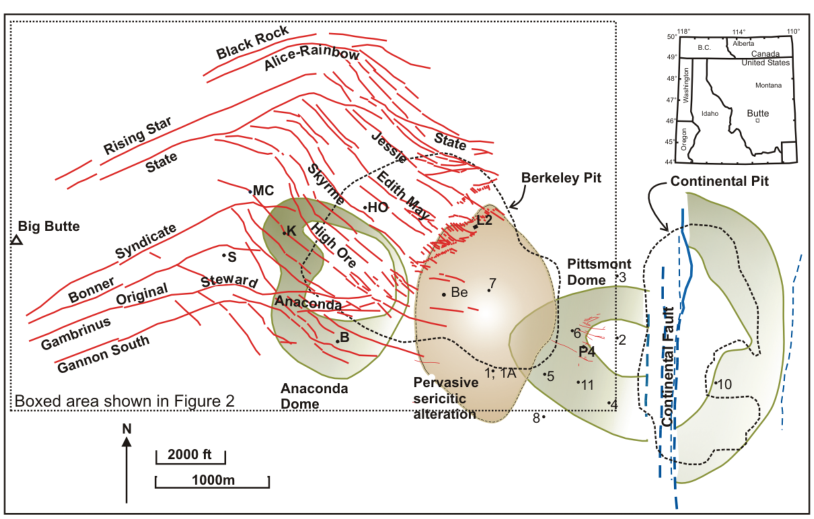

Figure 1. Location map and map of Main Stage and pre-Main Stage mineralization at Butte. Subsurface trace of Main Stage veins is shown in red and subsurface position of Pre-Main Stage porphyry Cu-Mo mineral centers, the Pittsmont and Anaconda domes, are shown in green. Also in the subsurface, a zone of pervasive sericitic alteration, separating the two mineral centers, is shown in tan. The locations of 10 deep drill holes are numbered in the Pittsmont dome. The locations of several mine shafts are also indicated; S= Steward, K= Kelly, MC= Mountain Consolidated, Be= Berkley, HO= High Ore, L2= Leonard, P4= Pittsmont #4, and B= Belmont. Boxed area is shown in Figure 2.

other deposits (Gustafson and Hunt, 1975; Seedorff et al., 2005). Early, dark micaceous (EDM of Meyer, 1965) veinlets are narrow quartz-chalcopyrite±pyrite veins with biotitic alteration that accompanied and followed dike intrusion (Meyer et al., 1968; Roberts, 1973, 1975; Brimhall, 1977). EDM veins are cut by molybdenite-bearing quartz-dominated veins with no alteration, which are cut by pyrite-quartz veins with sericitic alteration. All of these vein types are underlain by a core of barren quartz (±mo) veins with narrow K-feldspar (or less commonly biotitic) alteration haloes (Reed and Rusk, 2001; Rusk et al., 2008). Pre-Main Stage veins, their alteration, and their cutting relationships record the history of the Butte hydrothermal system from initial temperatures between 600° and 650°C and lithostatic pressures between 200 and 250 MPa corresponding to depths of 6 to 9 kilometers, to subsequent fluid cooling and decompression to temperatures near 370°C and transiently hydrostatic pressures between 40 and 70 MPa corresponding to depths between 4 and 7 kilometers (Roberts, 1975; Brimhall, 1977; Reed and Rusk, 2001; Field et al., 2005; Rusk et al., 2008).

Pre-Main Stage EDM and quartz-molybdenite veins are cut by the Modoc quartz-porphyry plug, which is cut by Main Stage mineralization. The relationship between pre-Main Stage pyrite-quartz veins and the Modoc porphyry is not known. Little new hydrothermal fluid accompanied emplacement of the Modoc porphyry as suggested by its weak mineralization, minimal alteration, and the lack of surrounding veins.

Main Stage mineralization

Main Stage veins are polymetallic base-metal lodes, some of which were up to 25 m in width, span up to 3.5 km across the district, and penetrate over 1.5 kilometers in depth. Centered above and west of the Anaconda dome (Fig. 1), steeply dipping Anaconda veins strike N60°E to N80°E and are offset by Blue veins that strike N40°W to N50°W (Fig. 1). At depth, Anaconda and Blue veins merge. Where the Blue veins border the central GS altered zone, they form a series of short en echelon gashes, known as the Horsetail vein zone. Rock textures including brecciation, overgrowth, mineral banding, and vein re-opening indicate that Main Stage veins are composite structures formed from multiple incursions of hydrothermal fluids. Sales and Meyer (1949) suggest that distinct structural epochs were not well defined, but that veins were formed through an ongoing process of structural movement and fluid incursion.

Sales (1914) delineated three roughly concentric major metal and mineralization zones at Butte (Fig. 2). The central zone is dominated by Cu mineralization, and lacks Zn mineralization. The intermediate zone contains veins mined for both Cu and Zn, and the peripheral zone has little Cu and was predominantly mined for Pb, Zn, Ag, and Mn (Fig. 3). Main Stage veins are also zoned from high-sulfur Cu-Fe-As-S mineral assemblages, including covellite, digenite, and enargite,

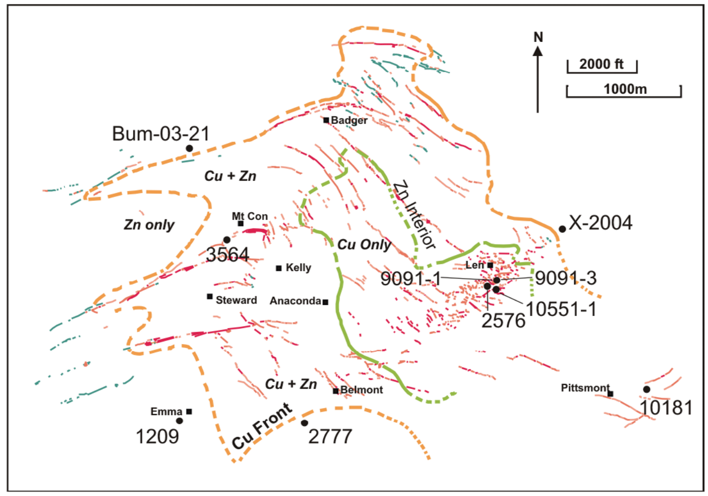

Figure 2. Map of Main Stage veins at the 3800 ft elevation level with central Cu zone, the intermediate Cu-Zn zone, and the peripheral Pb, Zn, Mn zone shown (C. Meyer, unpublished). Red veins were mined predominantly for Cu or Cu and Zn, while green veins were mined predominantly for Zn. Locations of ten of the samples discussed in this study are shown.

outward to progressively lower sulfur assemblages containing chalcopyrite, bornite, and tennantite in the intermediate zone and periphery. The trend indicates decreasing sulfidation state outward from the center of the deposit, but the zonation of sulfidation state is not strictly coincident with metal zonations. For example, the high sulfur assemblage is not restricted to the central zone and sphalerite may be present in any of the sulfidation assemblages (Meyer et al., 1968). In the peripheral zone, the main sulfides are sphalerite and galena with minor chalcopyrite and pyrite. Rhodochrosite is also common in the peripheral zone (Table 1).

Regardless of metal zone or vein age, Main Stage veins have inner sericitic alteration envelopes bordered by white argillic alteration in which plagioclase is replaced by

Table 1. Main Stage sample locations and minerals.

Sample number	Location and elevation[1]	Dominant minerals[2]
2576	Leonard 3200 level	en, dg, cc, qz, py, cp
9091-1	Leonard 3800 level	cv, dg, en qz, py
9091-3	Leonard 3800 level	cv, dg, en qz, py
10555-1	Berkeley Pit 4900 level	qz, en, cv, col
3564	Mountain Con 2300 level	qz, sl, py
2777	Belmont 3700 level	rc, py, sl, qz
x-2004	Elm Orlu 1000 level	qz, sl, rc, ca, cp, gn
10181	Columbia Gardens surface	qz, py, gn, cp
BUM-03-21	Lexington 2500 level	gn, sl, qz, py, cp
1209	Emma 400 level	qz, rc, sl, py, gn

[1]Elevation above sea level.

[2]Minerals listed in order of decreasing abundance. Abbreviations are as follows: calcite (ca), chalcopyrite (cp), chalcocite (cc) colusite (col), covellite (cv), digneite (dg), enargite (en), galena (gn), pyrite (py), quartz (qz), rhodochrosite (rc), sphalerite (sl).

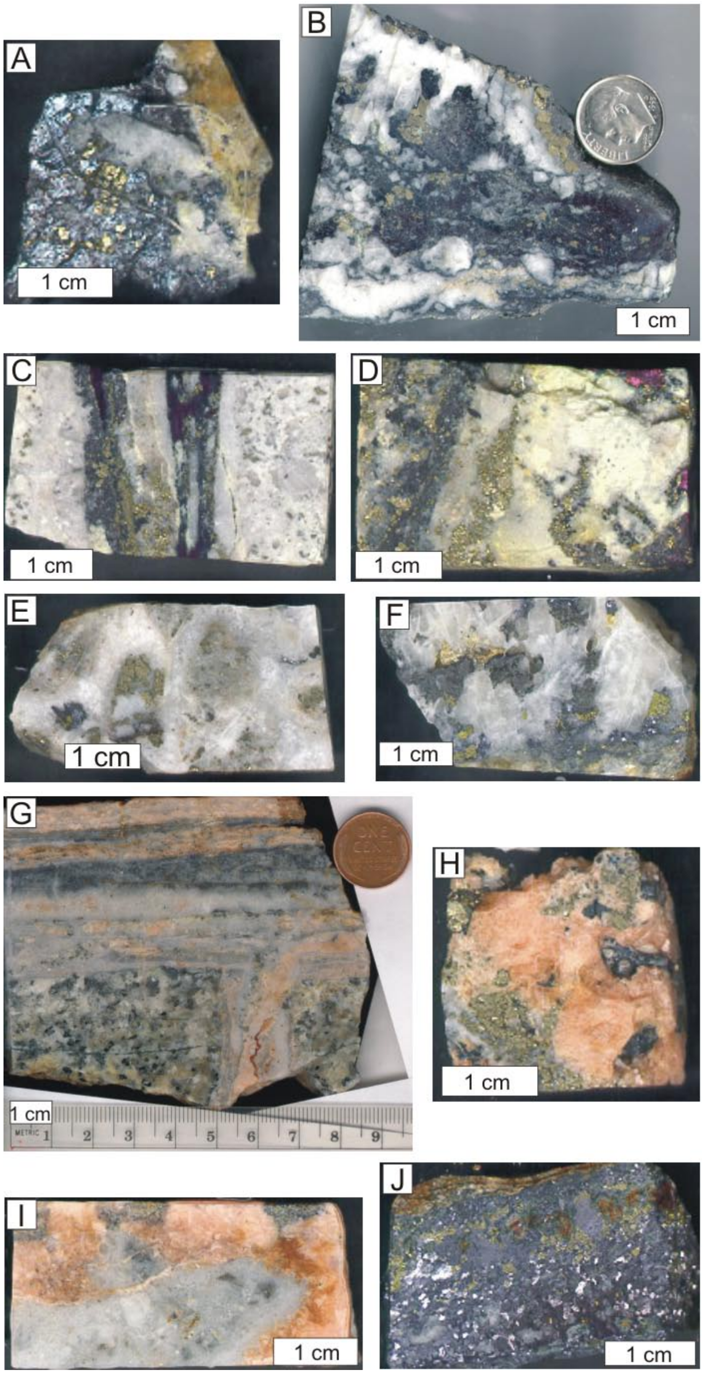

Figure 3. Hand samples of ten of the Main Stage veins analyzed by microthermometry. A) Central zone sample 2576 which contains en, dg, cc, qz, py, and cp; B) Central Zone sample 10555-1 which contains qz, en, cv, and col; C) Central zone sample 9091-3 which contains cv, dg, en, qz, and py; D) Central zone sample 9091-1 which contains cv, dg, en, qz, and py; E) Intermediate zone sample 3564 with brecciated fragments containing qz, sl, and py cemented by qz with minor sl; F) Peripheral zone sample 10181 which contains euhedral qz, py, gn, and cp; G) Peripheral zone sample X-2004 which is a banded vein with qz, sl, rc, ca, cp, and gn in BQM with intermediate argillic alteration; H) Peripheral zone sample 2777 which contains rc, py, sl, and qz; I) brecciated peripheral zone sample 1209 with matrix dominated by rc and qz with minor sl, py, and gn; J) Peripheral sample BUM-03-21 which is dominated by gn with lesser sl and qz and minor cp and py. See Table 1 for abbreviations.

kaolinite, and an outer zone of green argillic alteration where biotite and K-feldspar are fresh but plagioclase is replaced by smectite (Sales and Meyer, 1949). In the Leonard Horsetail Zone, advanced argillic alteration is locally abundant, giving way outward to pervasive sericitic alteration. Here, zunyite, dickite, alunite, and topaz are locally present (Meyer et al., 1968).

FLUID INCLUSIONS

Petrography

We examined ~50 Main Stage vein samples for mineral content and textures, and fluid-inclusion type, abundance, and distribution. Samples came from all mineralized zones spanning 7 km across the district and more than 1 km in vertical extent. Thirteen of these samples were selected for microthermometric analyses based on mineral zone, depth, and the presence of inclusions amenable for microthermometric analysis.

Unlike pre-Main Stage veins, euhedral quartz crystals are ubiquitous in Main Stage veins, and typically range in size from tens of microns to several centimeters (Figs. 3, 4). Primary fluid inclusions located along growth zones are common in Main Stage quartz, but many such inclusions are too small for microthermometry (Fig. 4). In addition to primary inclusions trapped along growth zones, secondary inclusions trapped along healed fractures are also present. In contrast to pre-Main Stage veins at Butte, fluid inclusion assemblages (cf. Goldstein and Reynolds, 1994) are easy to recognize in Main Stage veins. Textures and petrographic relations among minerals in Main Stage veins are complex. Many Main Stage veins are composite structures that are commonly brecciated and most show evidence for two or more generations of quartz growth in a single hand sample or thin section. Therefore, while primary fluid inclusions were trapped during quartz growth, they are not all necessarily directly related to ore-metal precipitation.

Scanning electron microscope - cathodoluminescent (SEM-CL) textures such as those shown in Figure 5 distinguish multiple episodes of quartz precipitation in Main Stage veins. These textures allow for specific generations of quartz and the inclusions they contain to be linked to ore-mineral precipitation. In this study our goal was to characterize the properties of fluid inclusions across a broad range of Main Stage veins throughout the deposit. We therefore did not attempt to relate specific fluid inclusions to mineralization events using cathodoluminescence. Future studies aimed at a detailed understanding of Main Stage mineralization should be constrained by quartz CL textures.

Fluid inclusions were identified in quartz, fluorite, rhodochrocite, and sphalerite. All Main Stage vein samples, regardless of location, depth, fluid-inclusion host mineral, or mineral zone, are dominated by a single fluid-inclusion type which contains an average of 20 volume % bubble at room

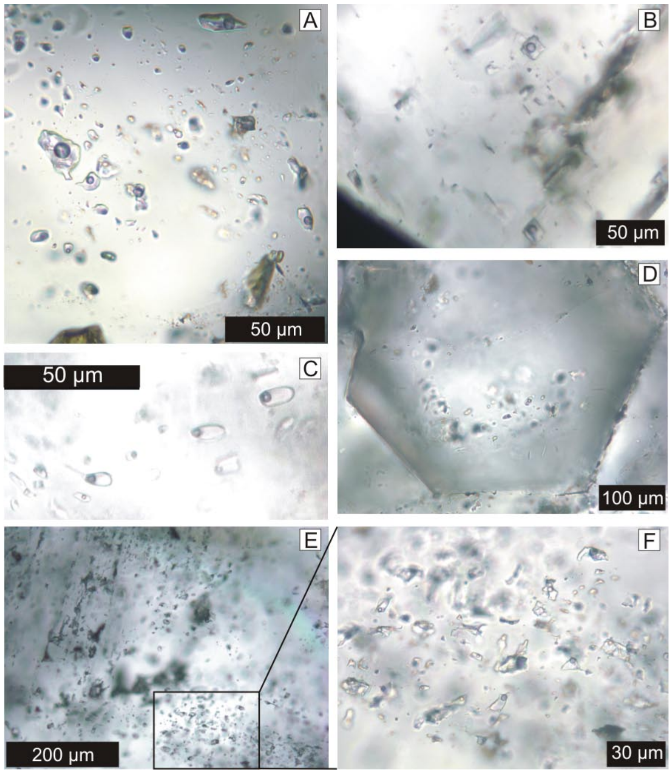

Figure 4. Fluid inclusions observed in this study. A) Primary B20 inclusions in quartz. B) B20 fluid inclusions in rhodochrosite. C) B20 fluid inclusions in fluorite. D) Euhedral quartz crystal with primary B20 inclusions in the interior of the crystal. E) Abundant primary fluid inclusions along growth zones in quartz. Many of these inclusions are irregular in shape, but liquid-to-vapor ratios among inclusions are constant. F) Close up of primary quartz-hosted B20s shown in E.

temperature (Fig. 4). We classify this inclusion type as a B20 fluid inclusion following the classification scheme of Rusk et al. (2008). B20 inclusions in Main Stage veins are commonly irregular in shape and rarely contain daughter minerals as is typical of other epithermal deposits (cf. Bodnar et al., 1985). No halite-saturated B15H (15 volume % bubble with a halite daughter mineral) fluid inclusions were identified in any Main Stage vein. Vapor-dominated B85 inclusions were identified in only one sample where several secondary trails containing only vapor-full inclusions were identified.

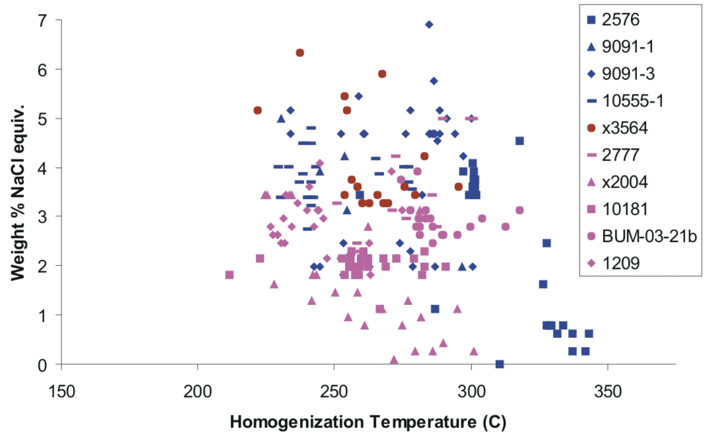

Figure 6. Homogenization temperature versus salinity for all inclusions for which both measurements were made. Salinities are calculated accounting for 0.2 mol % CO_2. Central zone samples are shown in blue, intermediate in brown, and peripheral zone samples are in pink. A slight trend from higher homogenization temperature and higher salinity in the central zone to lower homogenization temperature and salinity in the peripheral zone is apparent.

Compositions of Main Stage fluids

We conducted microthermometric analyses on ~350 fluid inclusions from 13 veins from the central, intermediate, and peripheral zones (Fig. 6). Although liquid CO_2 is never present at room temperature, and clathrate never forms upon cooling of the samples, the presence of CO_2 is identified in these inclusions by the expansion of vapor bubbles upon crushing in oil. The minimum concentration of CO_2 needed to be detected by this method is about 0.2 mol % (Bodnar et al., 1985) and at CO_2 concentrations greater than about 1 mol %, clathrate will form upon freezing (Rosso and Bodnar, 1995). These observations indicate that most Main Stage fluid inclusions contain between 0.2 and 1 mol% CO_2.

Ice melting in Main Stage fluid inclusions occurs at temperatures between 0.0°C and -4.7°C. Accounting for the presence of 0.2 mol % CO_2 (Hedenquist and Henley, 1985), these ice-melting temperatures correspond to salinities of 0.0 to 6.9

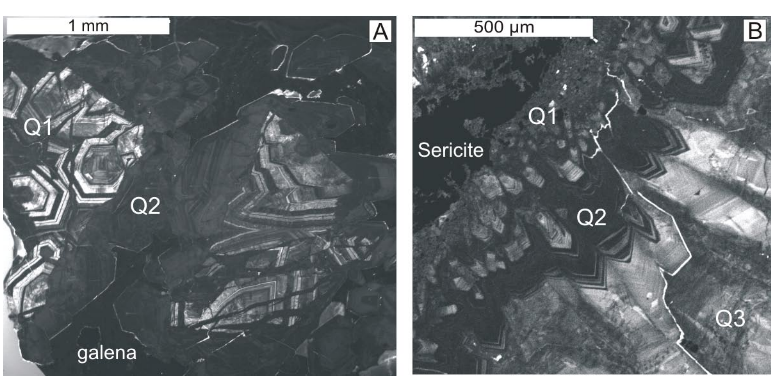

Figure 5. SEM-CL images of quartz from two Main Stage veins. A) SEM-CL image reveals two generations of quartz. Early Q1 quartz with oscillatory growth zones is cut by later Q2 quartz which is likely to be approximately contemporaneous with late galena mineralization. B) SEM-CL image showing three generations of quartz overgrowing sericite. Sericite alteration likely occurred before Q1 quartz.

wt. % NaCl equiv. with the vast majority of inclusions having salinities between 1 and 4 wt % NaCl equiv. B20 fluid inclusions from all Main Stage veins homogenize between ~140° and 350°C; however, homogenization temperatures lower than 220°C are restricted to inclusions in fluorite which is rare and paragenetically late.

Salinities and homogenization temperatures of fluid inclusions from the central, intermediate, and peripheral zone overlap widely (Fig. 6). Fluid inclusions from the central zone span the entire range of ice-melting temperatures from 0.0°C to -4.7°C, corresponding to salinities between 0.0 and 6.9 wt. % NaCl equiv. These inclusions homogenize at temperatures between 230°C and 350°C. Inclusions in the intermediate zone have ice-melting temperatures between -1.9°C and -4.3°C, corresponding to salinities between 3.3 and 6.3 wt. % NaCl equiv. These inclusions homogenize at temperatures between 230°C and 300°C. Inclusions from the peripheral zone have ice-melting temperatures between -0.4°C and -3.4°C, corresponding to salinities between 0.1 and 5 wt. % NaCl equiv., and they homogenize between 220°C and 320°C. Even though there is considerable overlap, there is a weak trend of decreasing homogenization temperatures and salinities from the central zone to the peripheral zone. Exceptions to this trend exist; for example most inclusions from peripheral-zone sample BUM 03-21b homogenize at higher temperatures than most inclusions from Central zone sample 9091-1, and most inclusions in central-zone sample 2576 have lower salinities than most inclusions in most peripheral-zone samples.

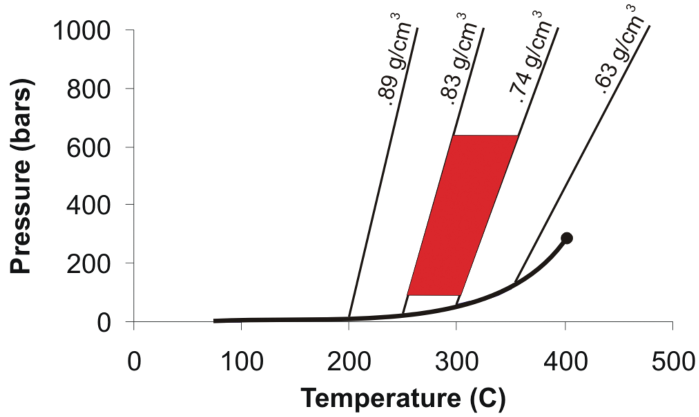

Figure 7. Pressure-temperature diagram showing inclusion density, and pressures and temperatures of trapping of most B20 inclusions in Main Stage veins. The isochores shown are of a 3 wt. % NaCl equiv. solution. Most Main Stage veins formed between 250°C and 350°C at pressures between 10 and 60 MPa.

DISCUSSION

Pressures and temperatures of Main Stage vein formation

All B20 inclusions from Main Stage veins homogenize to liquid, indicating that they were trapped above the liquid-vapor curve in the one-phase field. The addition of a small amount of CO_2 increases the pressure of the liquid-vapor curve slightly in the temperature range of interest (Gehrig et al., 1986). A few trails of secondary vapor-rich fluid inclusions identified in one sample from near the Leonard Horsetail zone could only have been formed by boiling of the hydrothermal fluid. No other evidence for boiling fluids such as bladed calcite crystals was identified, suggesting that boiling was rare and localized.

Because the vast majority of inclusions were trapped above the liquid-vapor curve, an isochoric correction must be applied to the homogenization temperature to derive the true pressure and temperature of Main Stage vein formation. In the absence of evidence for fluid boiling or other geologic constraints, pressure estimates are difficult to determine. In pre-Main Stage veins at Butte, pressure estimates are based on the intersection of fluid inclusion isochores with independently determined temperatures of vein formation (Roberts, 1975; Rusk et al., 2008). The latest pre-Main Stage veins are pyrite-quartz veins with sericitic alteration at pressures between 40 and 70 MPa and at temperatures between 370°C and 450°C. Main Stage veins always cut pyrite-quartz veins and most Main Stage veins are at shallower depths. We therefore infer that Main Stage veins formed at pressures below 60 MPa, but above the boiling curve.

Most Main Stage fluid inclusions contain between 1 and 4 wt. % NaCl equiv. and homogenize between 250°C and 300°C. Isochores for a 3 wt.% NaCl equiv. fluid indicate densities of 0.74 g/cm3 for inclusions homogenizing at 300°C and 0.83 g/cm3 for inclusions homogenizing at 250°C (Fig. 7). Based on a maximum pressure adjustment along these isochores to pressures of 60 MPa, the range of trapping conditions of most Main Stage fluid inclusions is between 250°C at ~10 MPa and 350°C at 60 MPa (Fig. 7). Slightly higher temperatures are likely for samples that have higher homogenization temperatures, and lower temperatures are likely for the formation of paragenetically late fluorite where homogenization temperatures are between 140°C and 220°C. Brittle deformation textures indicate hydrostatic pressures that correspond to depths between 1 and 6 km for the formation of Main Stage veins.

It is not clear from these results what physical or chemical processes resulted in the observed metal zoning pattern in Main Stage veins. A significant temperature decrease from the central zone toward the periphery is not obvious from fluid-inclusion homogenization temperatures, nor is there a dramatic change in fluid salinity, density, or gas content. The mineral and alteration assemblages are consistent with decreasing sulfidation state and increasing pH from the central zone outward, both of which might result from decreased fluid-to-rock ratio accompanied by sulfide precipitation. The range of homogenization temperatures suggests that significant fluid cooling from ~350°C to ~200°C occurred during the life span of Main Stage vein formation, but the peripheral zone seems to have achieved temperatures as high as the central zone and cooled through the same temperature range. These results do not rule out the role of temperature decrease in the formation of the observed mineral zones, but they do suggest that variations in fluid salinity and temperature were relatively minor among the mineralized zones. Low homogenization temperatures in fluorite from the intermediate zone indicate that timing of fluid-inclusion trapping is a critical factor that must be considered in order to understand the fluid evolution in the formation of Main Stage mineral zones. More detailed studies including cathodoluminescent textural analysis may help to match paragenetically contemporaneous quartz over the lateral spread of zones, which may help to resolve how fluid temperature and composition change with time relative to the mineral ore zones.

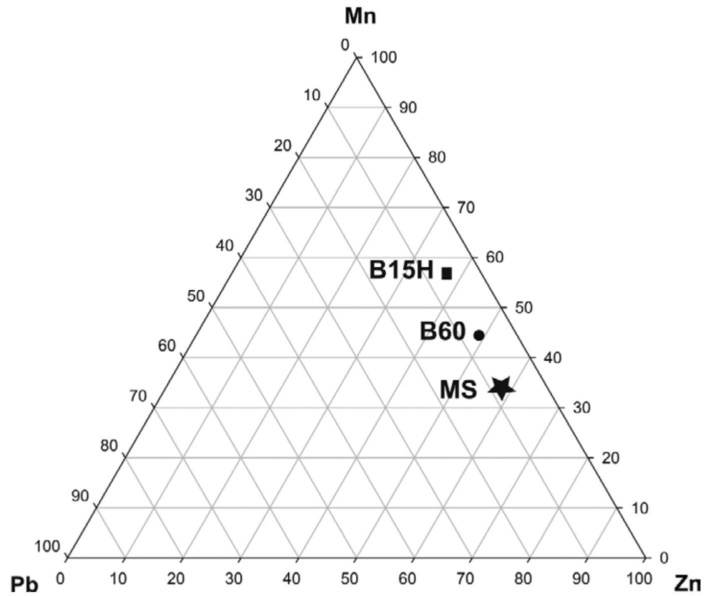

Figure 8. Ternary diagram showing the relative ratios of Zn, Mn, and Pb for bulk Main Stage mineralization, B60 inclusions, and B15H inclusions. B60 inclusions have Zn, Mn, and Pb ratios that are similar to Main Stage bulk metal ratios.

Origin of Main Stage mineralization

The relationship between pre-Main Stage and Main Stage mineralization is not well constrained. Brimhall suggested that Main Stage mineralization formed where meteoric fluids remobilized metals precipitated during pre-Main Stage mineralization (Brimhall, 1979, 1980). Oxygen isotopes, however, suggest that Main Stage veins formed from mixed magmatic and meteoric fluids (Zhang et al., 1999; Zhang, 2000). If Main Stage veins formed from mixed magmatic and meteoric waters, then it seems likely that Main Stage veins formed where rising and cooling magma-derived pre-Main Stage fluids mixed with circulating meteoric fluids.

Rusk et al., (2008) identified four fluid-inclusion types that dominate pre-Main Stage veins from Butte. In the deepest, potassically altered, quartz-rich veins, B35-type fluid inclusions trapped a single-phase fluid at temperatures between 575°C and 650°C and pressures between 200 and 250 MPa. As this fluid cooled and ascended, in some veins it unmixed forming B15H and B85 fluids and in other veins, the fluid cooled and depressurized, but remained above its solvus, trapping B60 fluid inclusions. If some pre-Main Stage fluids further evolved and contributed to Main Stage mineralization, then it is likely that such precursor Main Stage fluids are trapped in pre-Main Stage veins. Strong candidates should be rich in Cu, Pb, Zn, and Mn, and may contain these metals in ratios near the ratios of these metals in Main Stage veins.

Whereas halite-saturated B15H inclusions trapped in pre-Main Stage veins are rich in Mn, Zn, and Pb, with an average of 11,000 ppm Mn, 7,200 ppm Zn, and 1,200 ppm Pb, they contain only 1000 ppm Cu (Rusk et al., 2004). In addition to being Cu-depleted, ratios of Pb, Zn, and Mn in these inclusions are strikingly different than ratios of these metals in Main Stage veins (Table 2, Fig. 8). Furthermore, if fluids containing 40 wt. % NaCl equiv. had contributed significantly to Main Stage hydrothermal fluids, then a wider range of fluid salinities in Main Stage fluid inclusions should be present, depending on mixing ratio between magmatic and meteoric fluids. It does not appear likely therefore that the brine phase, formed upon fluid unmixing during porphyry-Cu mineralization, contributed to the metal endowment of Main Stage veins.

Vapor that formed from brine-vapor unmixing might have contributed to Main Stage vein formation, but no data on the metal concentrations of vapor-rich inclusions from Butte exists. Salinities of pre-Main Stage vapors (0-3 wt. % NaCl equiv.; Rusk et al., 2008) do not preclude their contribution to Main Stage vein formation.

Pre-Main Stage pyrite-quartz veins with sericitic altera-

Table 2. Metal concentrations in Main Stage veins and pre-Main Stage fluid inclusions.

	Cu	Zn	Mn	Pb
Main Stage total metals (Mtonnes)[1]	~11	2.9	1.7	0.4
B60 inclusions (ppm)[2]	7000	420	380	60
B15H inclusions (ppm)[2]	1000	7200	11000	1200

[1]Long, 1995
[2]Rusk et al., 2004

tion are dominated by low salinity (2-5 wt. % NaCl equiv.) CO_2-bearing fluid inclusions trapped at temperatures between 370° and 450°C and pressures between 40 and 70 MPa (Rusk et al., 2008). The formation of pyrite-quartz veins with sericitic alteration is the latest, shallowest, and coolest pre-Main Stage mineralization event. Pyrite quartz-veins are dominated by B60 fluid inclusions, which are enriched by up to an order of magnitude in Pb, Zn, and Mn relative to earlier and deeper pre-Main Stage B35 inclusions (Rusk et al., 2004). Even though pyrite-quartz veins with sericitic alteration postdate pre-Main Stage Cu mineralization at Butte, they are metal-rich and contain an average of ~7000 ppm Cu, ~380 ppm Mn, ~420 ppm Zn, and ~60 ppm Pb. Ratios of Cu, Pb, Zn, and Mn in these inclusions are similar to ratios of these metals mined from Main Stage veins (Table 2; Fig. 8). Pyrite-quartz veins are closer to Main Stage veins in temperature, pressure, time, space, and fluid composition than any other mineralization event at Butte. Magma-derived fluids trapped in B60 inclusions are likely to have contributed metals and volatiles to the hydrothermal system that formed Main Stage veins. We suggest that as these fluids ascended, they continued to cool and depressurize and mixed with circulating meteoric fluids and formed Main Stage veins.

CONCLUSIONS

Fluid inclusions in veins from the Central Cu zone, the intermediate Cu-Zn zone, and peripheral Pb, Zn, Mn (Ag) zone are remarkably similar in salinity, density, and homogenization temperature. With the exception of fluids trapped in late fluorite, most fluid inclusions in Main Stage veins have densities between 0.74 and 0.83 g/cm^3, contain 0.2 to 1 mol % CO_2, 1-4 wt. % NaCl equiv., and homogenize between 250°C and 300°C. With only rare and localized evidence for boiling, most fluid inclusions were trapped at pressures above the boiling curve and below 60 MPa at temperatures between 250°C and 350°C. There is significant overlap in salinities and homogenization temperatures between the central, intermediate, and peripheral zones, but there is a weak trend from higher salinities and temperatures in the center to lower salinities and temperatures in the periphery.

We suggest that Main Stage veins and pre-Main Stage veins are genetically related and that the differences between them result from the evolving pressure and temperature regime of the Butte hydrothermal system. Main Stage veins formed as fluids that formed pre-Main Stage pyrite-quartz veins with sericitic alteration continued to cool and depressurize and mixed with circulating meteoric fluids under hydrostatic pressures. Metal-rich brines apparently did not contribute significantly to Main Stage vein formation, and the role of pre-Main Stage vapors in the formation of Main Stage veins is not known.

ACKNOWLEDGMENTS

This research was funded by a USGS Mendenhall postdoctoral Fellowship to Brian Rusk and by NSF EAR-0001272 and EAR- 0440198, part of which supported Brooke Miller's Masters research at the University of Oregon. We thank John Dilles, Al Hofstra, and Bob Rye for discussions and comments, and Dick Berg, Linda Albright, and Steve Czehura were instrumental in helping us obtain samples.

REFERENCES CITED

Arribas, A, Jr., Hedenquist, J.W., Itaya, T., Okada, T., Concepcion, R.A., and Garcia, J.S., Jr., 1995, Contemporaneous formation of adjacent porphyry and epithermal Cu-Au deposits over 300 ka in Northern Luzon, Phillipines: Geology, v. 23, p. 337-340.

Bodnar, R.J., Reynolds, T.J., and Kuehn, C.A., 1985, Fluid inclusion systematics in epithermal systems, *in* Berger, B.R., and Bethke, P.M., eds., Geology and Geochemistry of Epithermal Systems: Society of Economic Geologists, Reviews in Economic Geology, v. 2, p. 73-98.

Brimhall, G.H., Jr., 1977, Early fracture-controlled disseminated mineralization at Butte, Montana: Economic Geology, v. 72, p. 37-59.

Brimhall, G.H., Jr., 1979, Lithologic determination of mass transfer mechanisms of multiple-stage porphyry copper mineralization at Butte, Montana: Vein formation by hypogene leaching and enrichment of potassium silicate protore: Economic Geology, v. 74, p. 556-589.

Brimhall, G.H., 1980, Deep hypogene oxidation of porphyry copper potassium-silicate protores: A theoretical evaluation of the copper remobilization hypothesis: Economic Geology, v. 75, p. 384-409.

Corn, R.M., 1975, Alteration-mineralization zoning, Red Mountain, AZ: Economic Geology, v. 70, p. 1437-1447.

Czehura, S., 2006, Butte: A world class ore deposit: Mining Engineering, September issue, p. 14-19.

Einaudi, M.T., 1994, Report on SEG International Exchange Lecturer Tour: Japan-Korea-Philippines, June 1994: Society of Economic Geologists Newsletter 19, p. 21–26.

Einaudi, M.T., Hedenquist, J.W., and Inan, E.E., 2003, Sulfidation state of fluids in active and extinct hydrothermal systems: Transitions from porphyry to epithermal environments: Society of Economic Geologists Special Publication 10, p. 285–313.

Field, C.W., Zhang, L., Dilles, J.H., Rye, R.O., and Reed, M.H., 2005, Sulfur and oxygen isotopic record in sulfate and sulfide minerals of early, deep, pre-Main Stage porphyry Cu-Mo and late, shallow Main Stage base-metal mineral deposits, Butte district, Montana: Chemical Geology, v. 215, p. 61-93.

Gehrig, M., Lentz, H., and Franck, E., 1986, The system water-carbon dioxide-sodium chloride to 773 K and 300 MPa: Physical Chemistry, v. 90, p. 525-533.

Goldstein, R.H., and Reynolds, T.J., 1994, Systematics of fluid inclusions in diagenetic materials: Society for Sedimentary Geology Short Course 31, 199 p.

Gustafson, L.B., and Hunt, J.P., 1975, The porphyry copper deposit at El Salvador, Chile: Economic Geology, v. 70, p. 857-912.

Hedenquist, J., and Henley, R., 1985, The importance of CO_2 on freezing point measurements of fluid inclusions: Evidence from active geothermal systems and implications for epithermal ore deposition: Economic Geology, v. 80, p. 1379-1406.

Hedenquist, J., Arribas, A., and Reynolds, J., 1998, Evolution of an intrusion-centered hydrothermal system: Far Southeast-Lepanto porphyry and epithermal Cu-Au deposits, Philippines: Economic Geology, v. 93, p. 373-404.

Khashgerel, B., Rye, R.O., Hedenquist, J.W., and Imants, K., 2006, Geology and reconnaissance stable isotope study of the Oyu Tolgoi porphyry Cu-Au system, South Gobi, Mongolia: Economic Geology, v. 101, p. 503-522.

Long, K.R., 1995, Production and reserves of Cordilleran (Alaska to Chile) porphyry copper deposits, *in* Pierce, F.W., and Bolm, J.G., eds., Porphyry copper deposits of the American Cordillera: Arizona Geological Society Digest 20, p. 35-68.

Manske, S.L., and Paul, A.H., 2002, Geology of a major new porphyry copper center in the Superior (Pioneer) district, Arizona: Economic Geology, v. 97, p. 197-220.

Meyer, C., 1965, An early potassic type of wall rock alteration at Butte, Montana: American Mineralogist, v. 50, p. 1717-1722.

Meyer, C., Shea, E., Goddard, C., and Staff, 1968, Ore deposits at Butte, Montana: in Ridge, J.D. ed., Ore Deposits of the United States 1933-1967 (Graton-Sales vol.): New York, American Institute of Minerals, Metals, and Petroleum Engineers, v. 2, p. 1363-1416.

Miller, B.J., 2004, Aqueous fluid inclusions in the Butte, Montana, Main Stage vein system: M.S. thesis, University of Oregon, 101 p.

Ossandon, C.G., Freraut, C.R., and Gustafson, L.B., 2001, Geology of the Chuqicamata mine: A progress report: Economic Geology, v. 96, n. 2, p. 249-270.

Muntean, J.L., and Einaudi, M.T., 2001, Porphyry-epithermal transition: Maracunga belt, northern Chile: Economic Geology, v. 96, p. 743-772.

Phillips, C.H., Smith, T.W., and Harrison, E.D., 1998, Alteration metal zoning and ore controls in the Bingham Canyon porphyry copper deposits, Utah, *in* John, D.A., and Ballantyne, G.H., eds., Geology and Ore Deposits of the Oquirrh and Wasatch Mountains, Utah: Society of Economic Geologists Guidebook Series v. 29, p.133-145.

Reed, M., and Rusk, B., 2001, Insights into supercritical hydrothermal processes from numerical models of potassic hydrothermal alteration, and SEM-CL imaging of vein quartz at Butte, Montana, *in* Toshiyuki, H., ed., Proceedings from the workshop on potential thermal extraction from deep-seated rock masses: Tohoku University, Japan, p. 37-53.

Roberts, S.A., 1973, Pervasive early alteration in the Butte district, Montana, *in* Miller, R. N. ed., Society of Economic Geologists, Butte field meeting guidebook, The Anaconda Company, p. HH1-HH8.

Roberts, S.A., 1975, Early hydrothermal alteration and mineralization in the Butte district, Montana: Ph.D. dissertation, Harvard University, 157 p.

Roedder, E., 1971, Fluid inclusion studies on the porphyry-type ore deposits at Bingham, Utah, Butte, Montana, and Climax, Colorado: Economic Geology, v. 66, p. 98-120.

Rosso, K.M., and Bodnar, R.J., 1995, Microthermometric and Raman spectroscopic detection limits of CO_2 in fluid inclusions and the Raman spectroscopic characterization of CO_2: Geochimica et Cosmochimica Acta., v. 59, p. 3961-3975.

Rusk, B., Reed, M., Dilles, J.H., Klemm, L, and Heinrich, C.A., 2004, Compositions of magmatic hydrothermal fluids determined by LA-ICP-MS of fluid inclusions from the porphyry copper-molybdenum deposit at Butte, Montana: Chemical Geology, v. 210, p. 173-199.

Rusk, B., Reed, M., and Dilles, J.H., 2008, Fluid inclusion evidence for magmatic-hydrothermal fluid evolution in the porphyry copper-molybdenum deposit, Butte, Montana: Economic Geology, v. 103, p. 307-334.

Sales, R.H., 1914, Ore deposits at Butte, Montana: American Institute of Mining and Metallurgical Engineering Transactions, v. 46, p. 3-109.

Sales, R.H., and Meyer, C., 1949, Results from preliminary studies of vein formation at Butte, Montana: Economic Geology, v. 44, p. 465-484.

Seedorff, E., Dilles, J.H., Proffett, J.M., Einaudi, M.T., Zurcher, L., Stavast, W.J. A., Johnson, D.A., and Barton, M.D., 2005, Porphyry deposits: characteristics and origin of hypogene features: Economic Geology 100th Anniversary Volume, p. 251-298.

Zhang, L., Dilles, J.H., Field, C.W., and Reed, M.H., 1999, Oxygen and hydrogen isotope geochemistry of pre-Main Stage porphyry Cu-Mo mineralization at Butte, Montana [abs.]: Geological Society of America Abstracts with Programs, v. 31, n. 7, p. A381.

Zhang, L., 2000, Stable isotope investigation of a hydrothermal alteration system; Butte porphyry copper deposit: Ph.D. dissertation, Oregon State University, 182 p.